Climate Change Detection and Attribution: A Personal View of the Emerging Science

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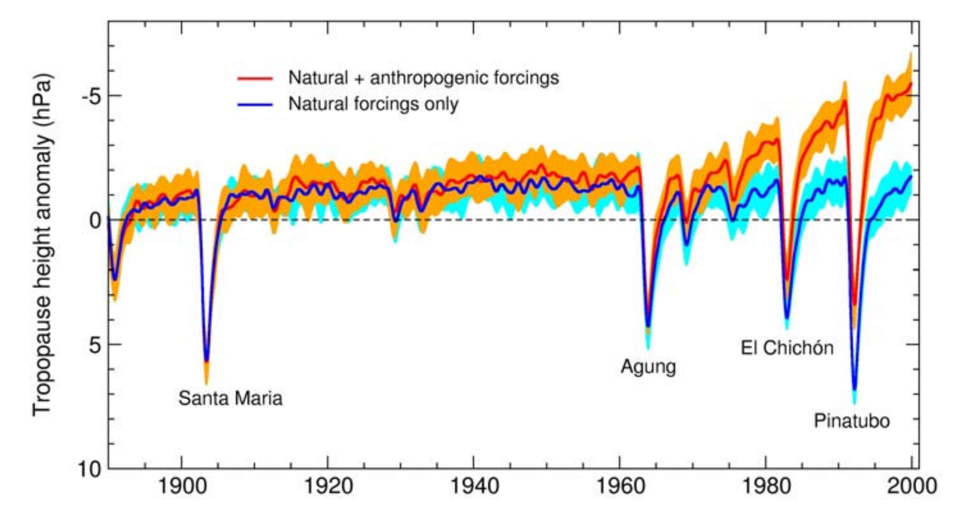
First Annual Conference on Climate Change
From Climate to Economics: Anticipating Impacts of Climate Change in California
Sacramento, CA, June 9th, 2004

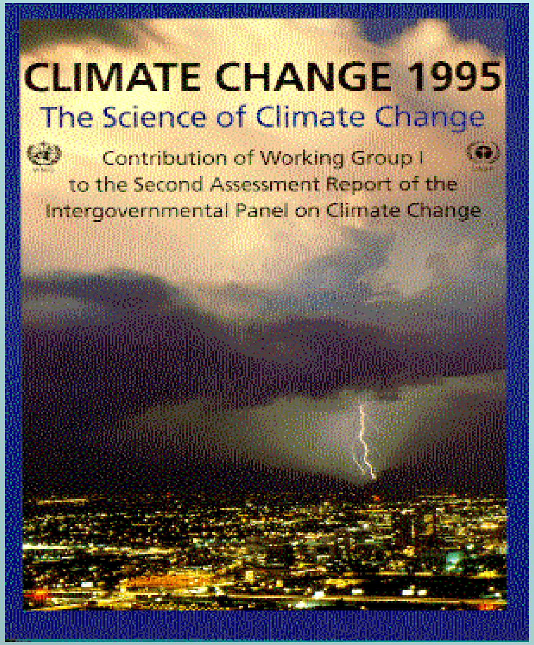


PCMDI

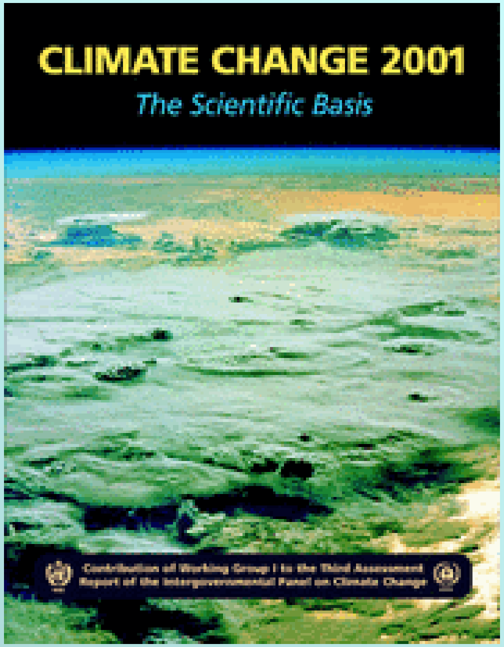
Structure of talk

- Climate change 101: A brief primer
- Climate model evaluation
- Emerging science (a biased personal view)
- Conclusions

Key findings of the Intergovernmental Panel on Climate Change: Humans are affecting Earth's climate



"The balance of evidence suggests a discernible human influence on global climate"

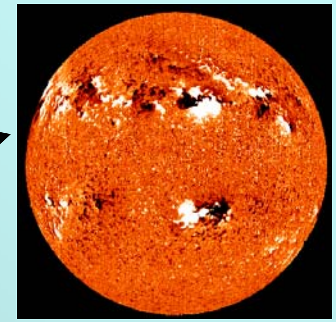


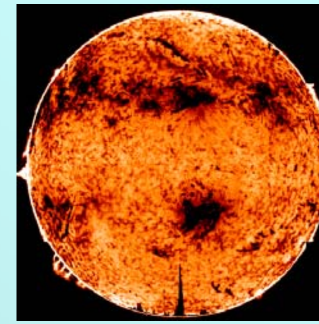
"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities"

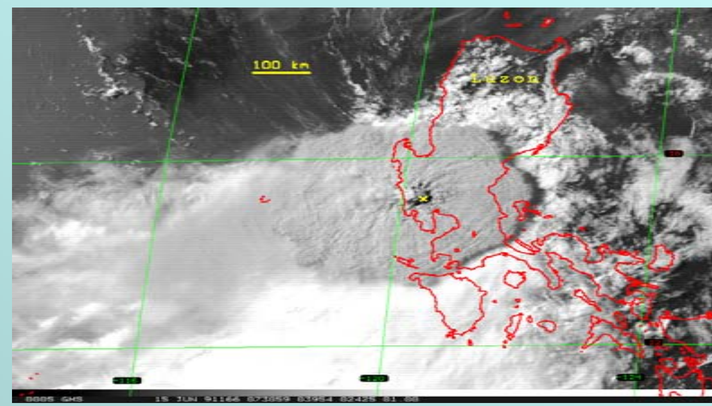
Climate Change 101: Natural mechanisms influence climate

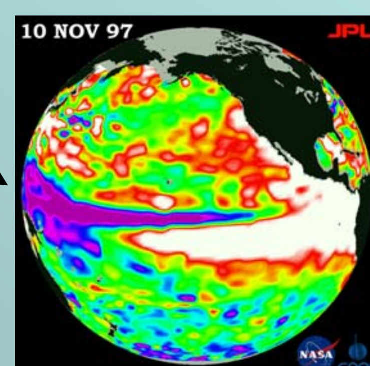
Natural mechanisms

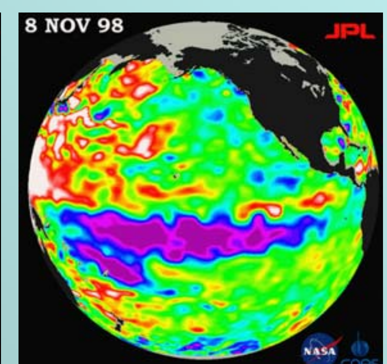
- Changes in the Sun
- Changes in the amount of volcanic dust in the atmosphere
- Internal variability of the coupled atmosphere-ocean system







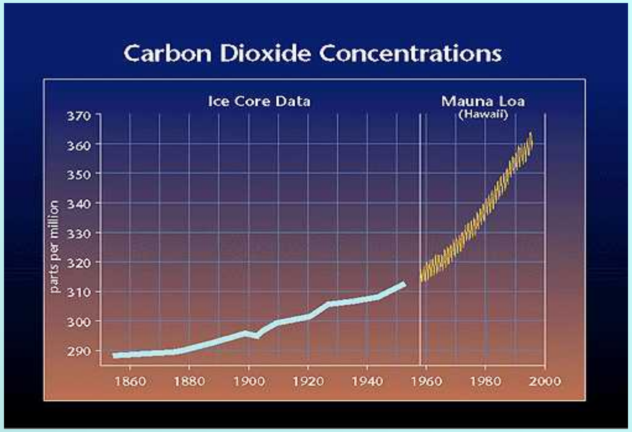


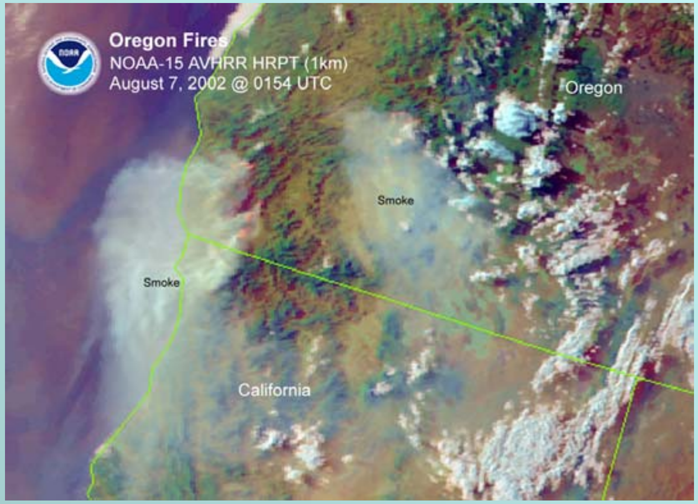


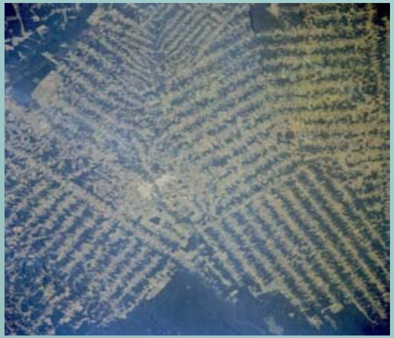
Climate Change 101: Human factors also influence climate

Non-natural mechanisms

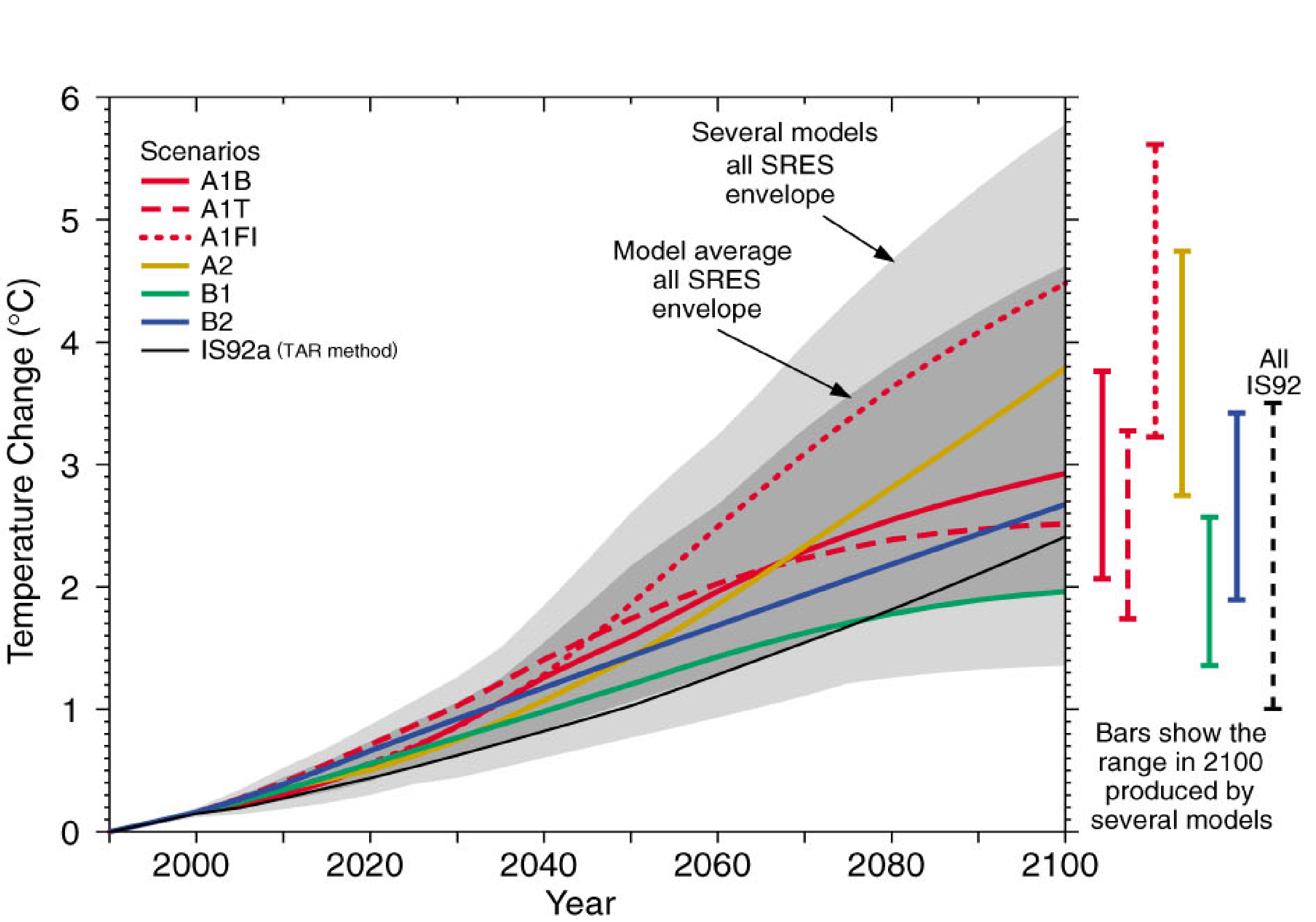
- Changes in atmospheric concentrations of greenhouse gases
- Changes in aerosol particles from burning fossil fuels and biomass
- Changes in the reflectivity (albedo) of the Earth's surface







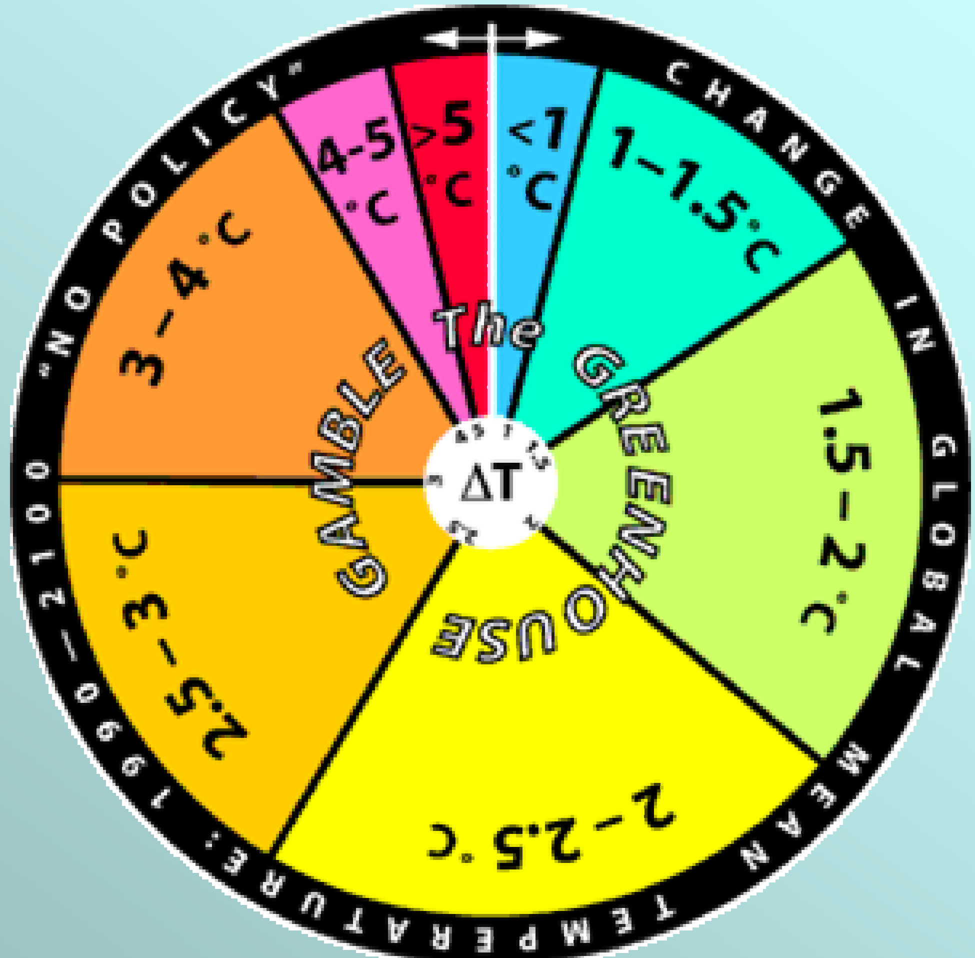
Climate Change 101: There are large uncertainties in projections of future global-mean temperature changes



* Source: IPCC Third Assessment Report, Summary for Policymakers

The great “greenhouse gamble”…

<1°C	(4.1%; 1 in 24 odds)
1 to 1.5°C	(11.4%; 1 in 9 odds)
1.5 to 2°C	(20.6%; 1 in 5 odds)
2 to 2.5°C	(22.5%; 1 in 4 odds)
2.5 to 3°C	(16.8%; 1 in 6 odds)
3 to 4°C	(16.2%; 1 in 6 odds)
4 to 5°C	(4.6%; 1 in 22 odds)
>5°C	(3.8%; 1 in 26 odds)



Source: MIT Joint Program on the Science and Policy of Climate Change

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- **Climate model evaluation**
- Emerging science (a biased personal view)
- Conclusions

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Why is climate model evaluation important?

- Climate models are the only tool we have for making predictions about the climate change “signal” that may result from human-caused increases in atmospheric CO_2
- These tools have systematic errors
- These errors limit our ability to make reliable forecasts of the climate changes we may experience over the next century

How do we evaluate climate models?

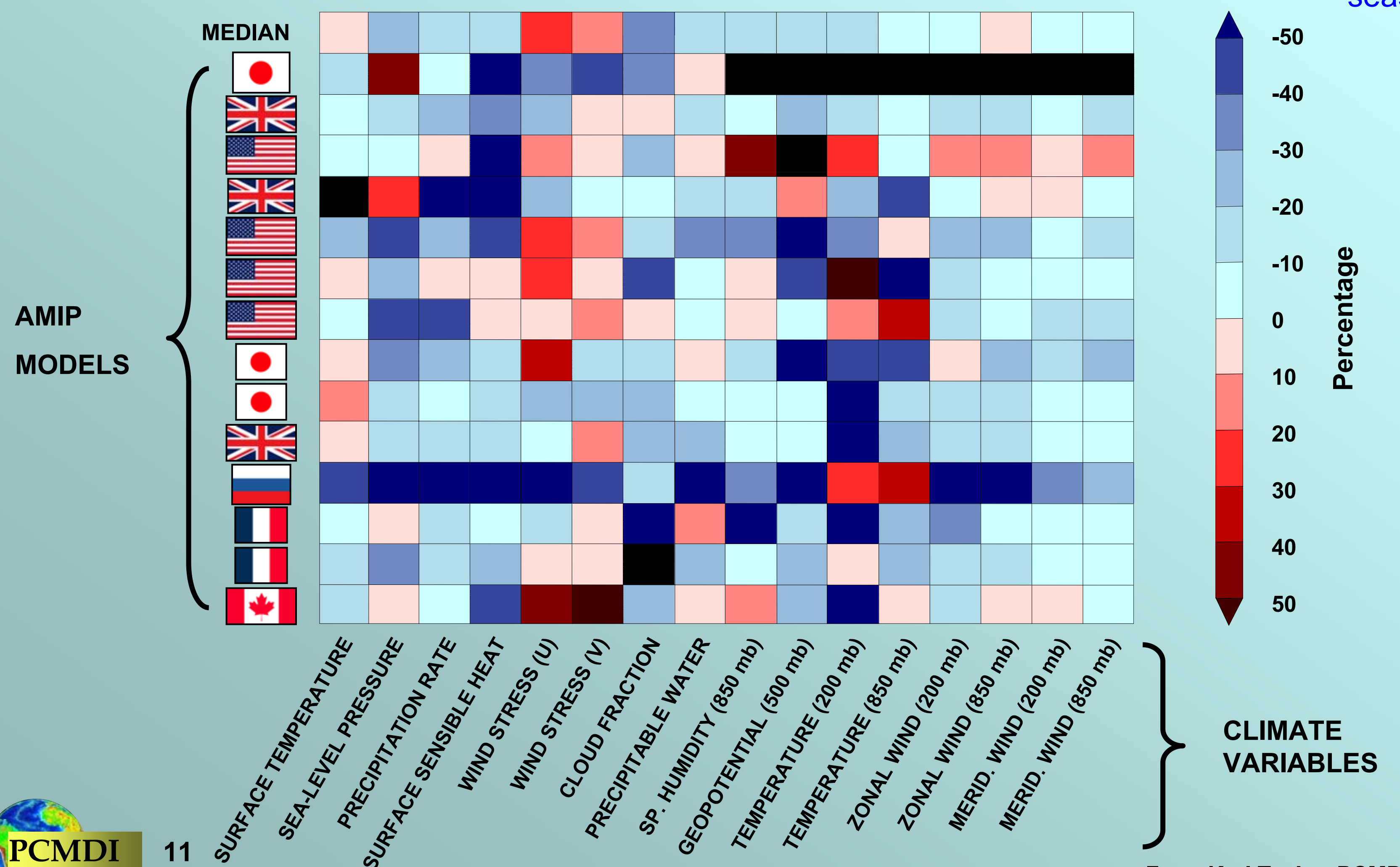
Types of test

- Today's annual mean climate
- The diurnal cycle
- The seasonal cycle
- Interannual variability (El Niño, North Atlantic Oscillation, etc.)
- The climate of the past 50-150 years
- Climates of the distant past (e.g., the last Ice Age)

Atmospheric models have improved over time

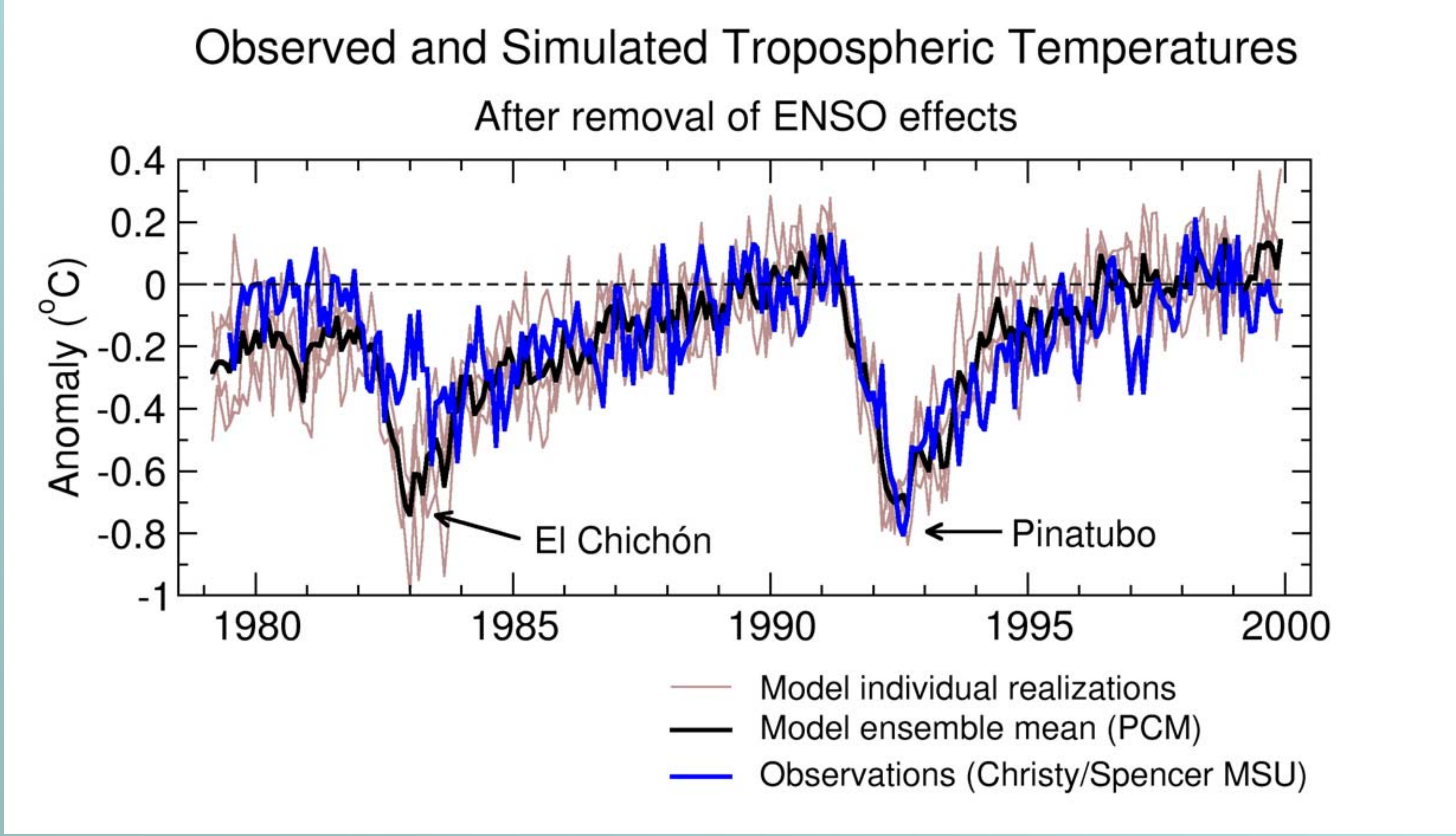
Percentage change in total error (AMIP2-AMIP1)

Global, all seasons



From Karl Taylor, PCMDI

Another test: Can models simulate the temperature changes after major volcanic eruptions?



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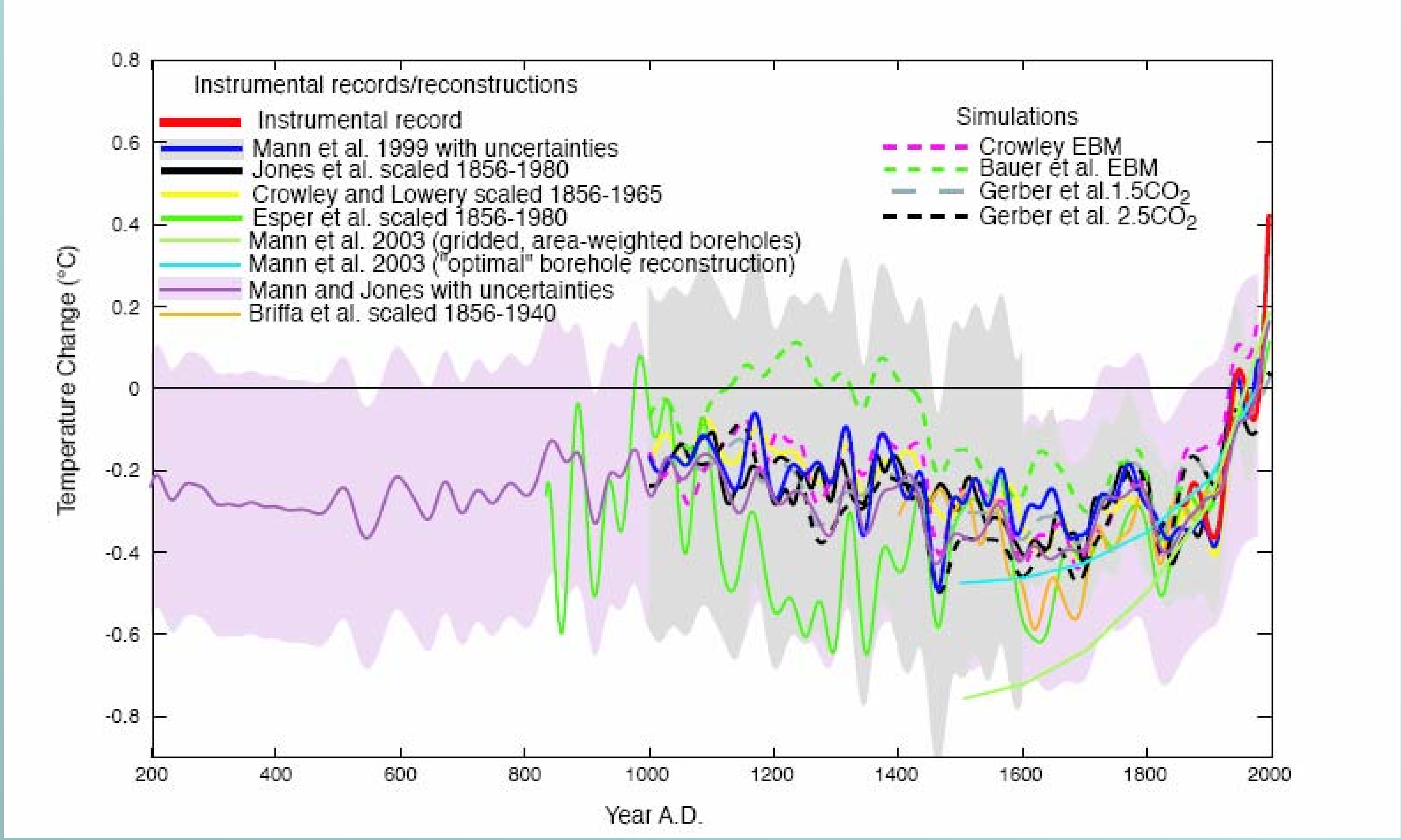
We now have a variety of estimates of temperature changes over the last 1-2 millenia



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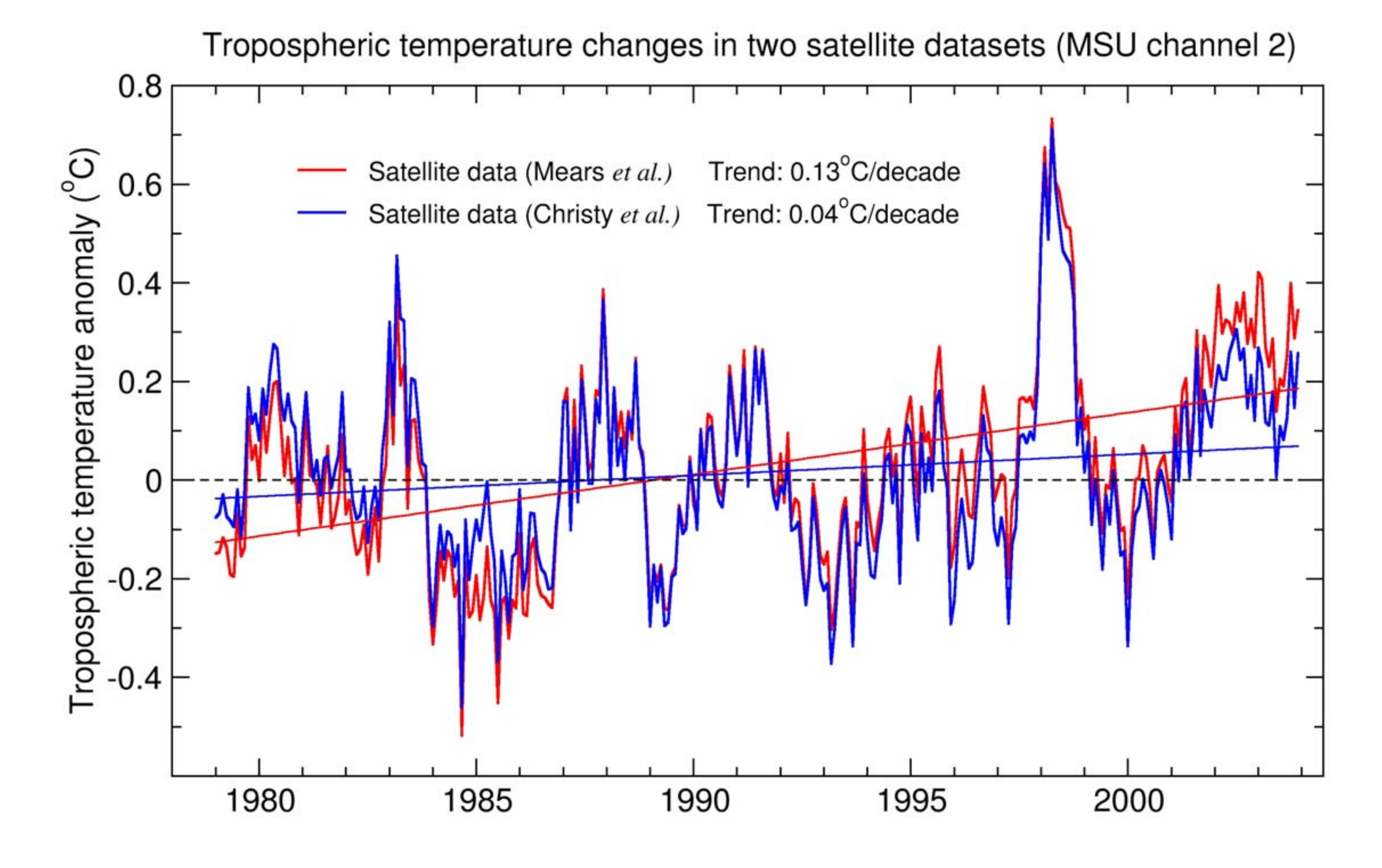
We have made progress in resolving an important problem: The apparent lack of tropospheric warming

"And we know that the theory that increasing concentrations of greenhouse gases like carbon dioxide will lead to further warming is at least an oversimplification. It is inconsistent with the fact that satellite measurements over 35 years show no significant warming in the lower atmosphere, which is an essential part of the global-warming theory".

James Schlesinger (former Secretary of Energy, Secretary of Defense, and Director of the CIA), "Cold Facts on Global Warming", L.A. Times, January 22, 2004

We now have multiple estimates of temperature change in the troposphere



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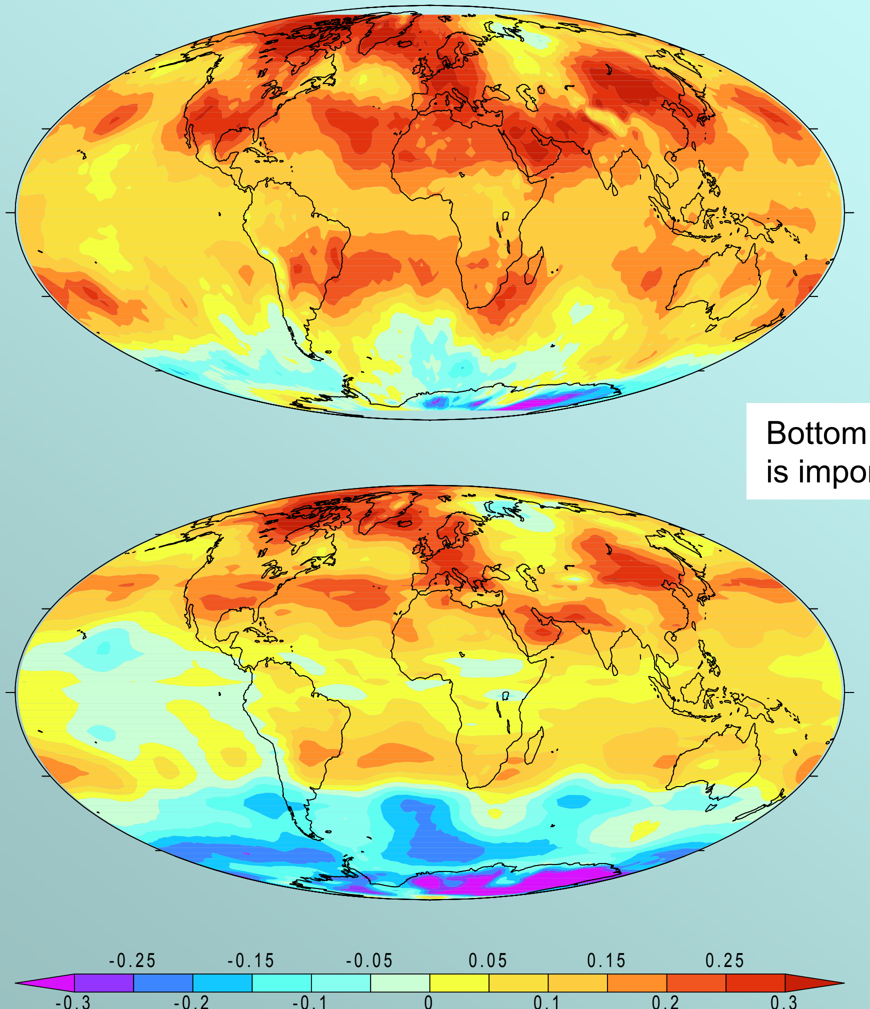
Tropospheric temperature trends over 1979-2003 in two different satellite datasets

Mears *et al.*

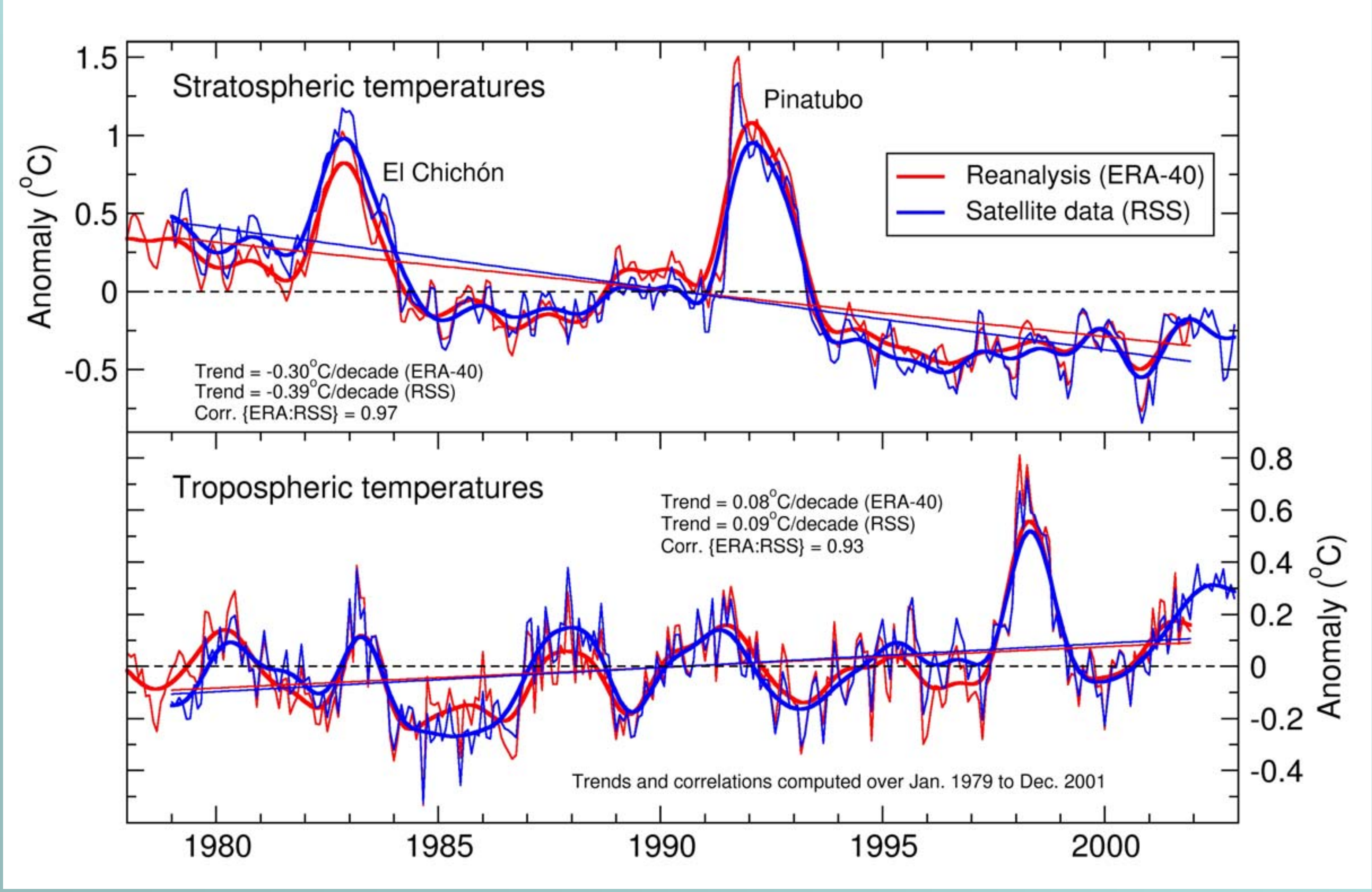
Christy *et al.*



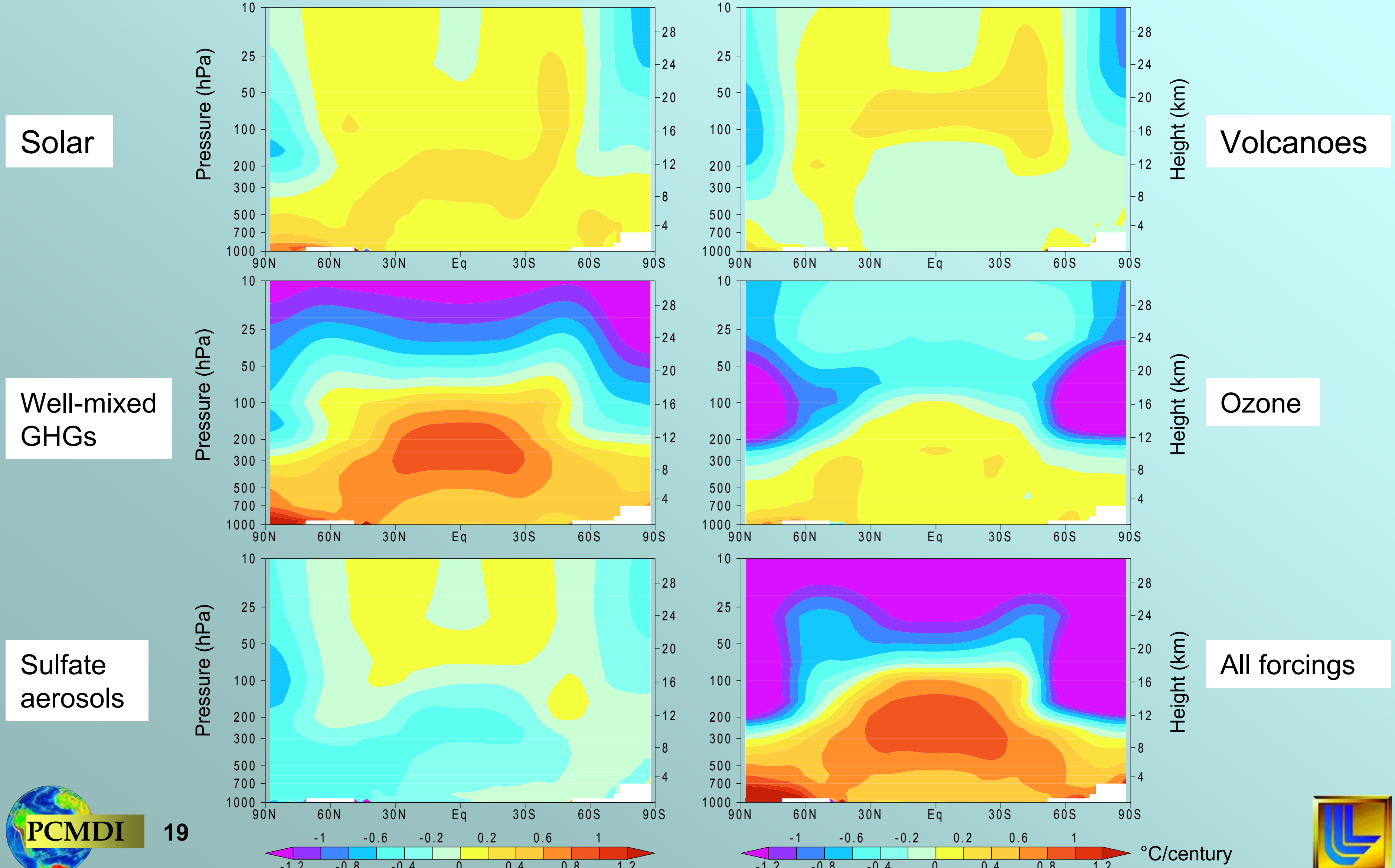
Linear trend (°C/decade)

Bottom line: Observational uncertainty is important in model evaluation work!

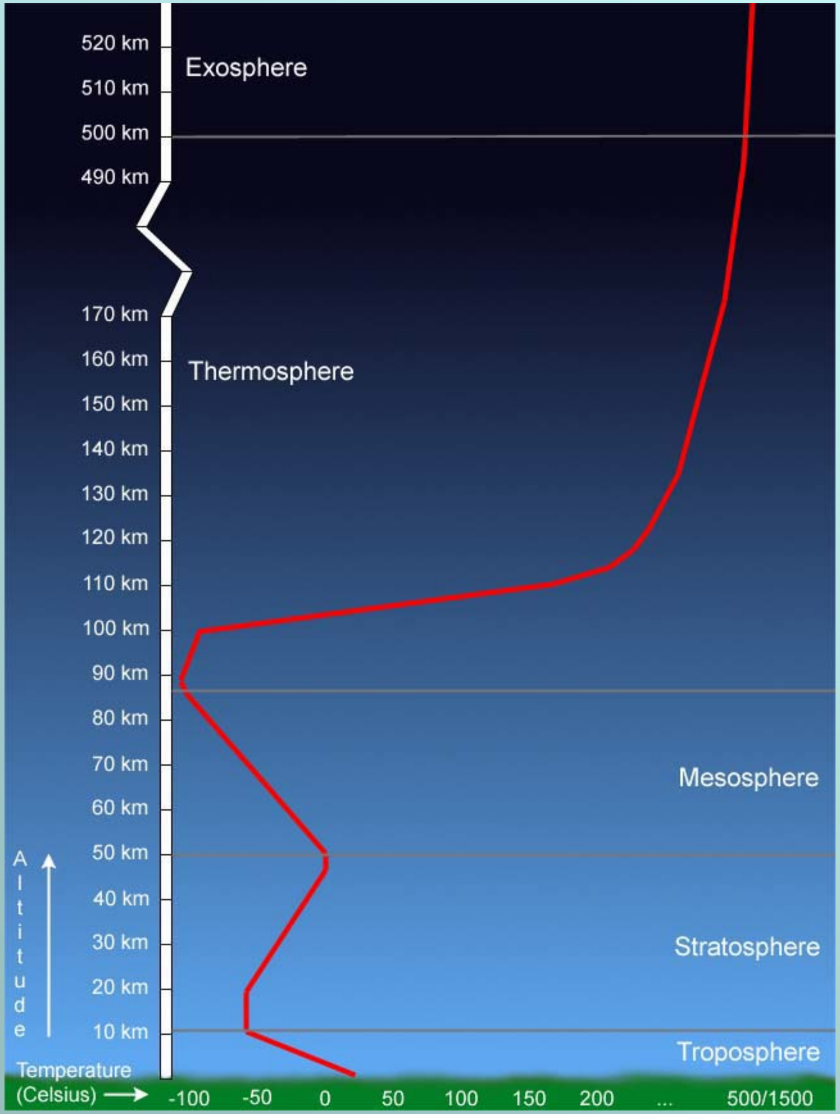
Other estimates of atmospheric temperature change are now becoming available

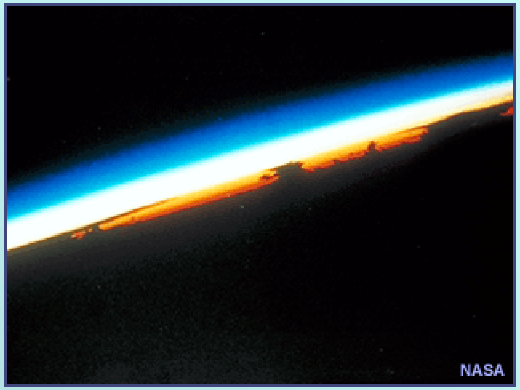


We are making progress in defining the characteristic “fingerprints” of different climate forcings

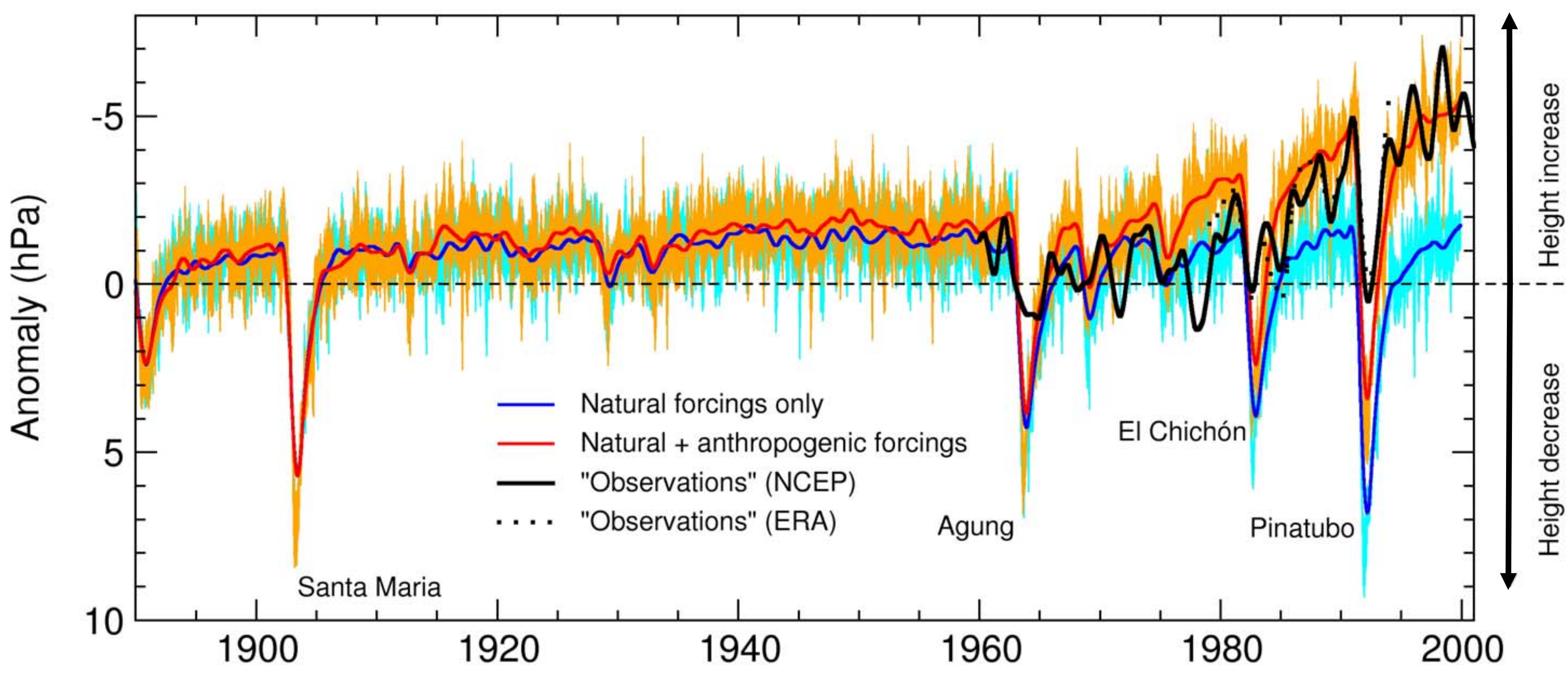


We are identifying new “fingerprints” of human effects on climate: Tropopause height





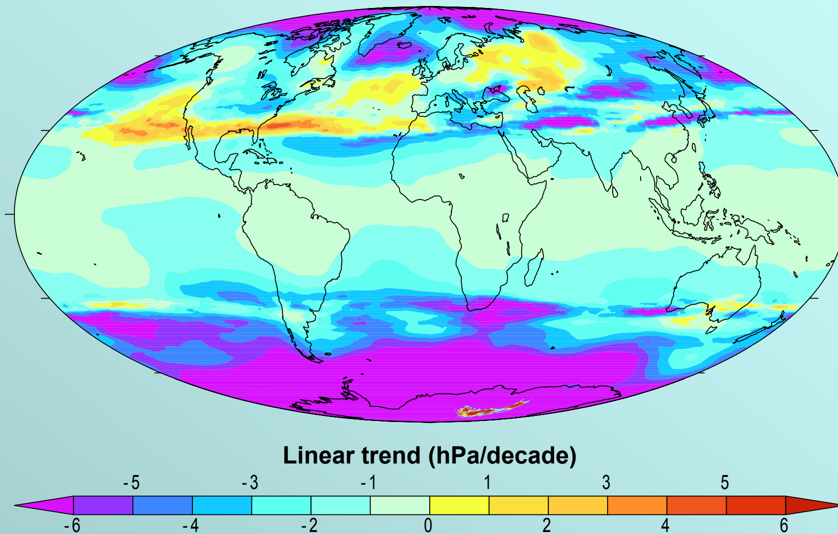
In a climate model, human-caused changes in tropopause height are large relative to natural effects



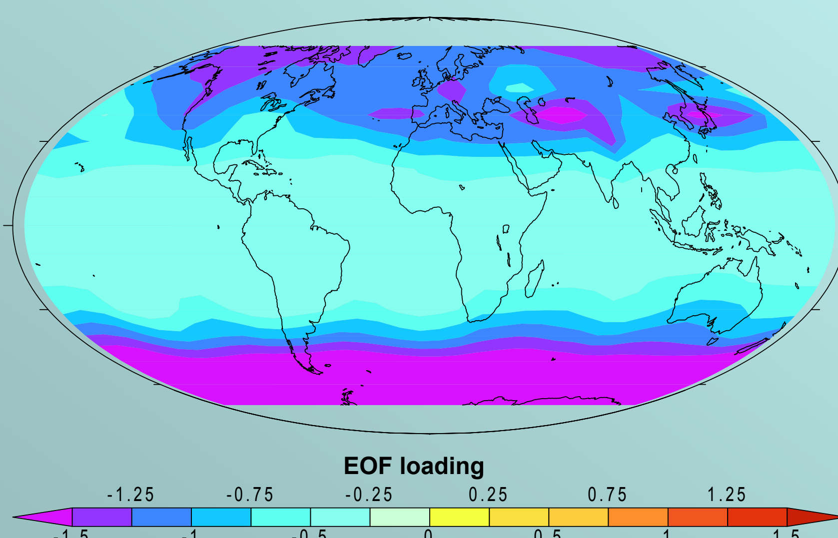
Santer *et al.*, *Science* (2003)

Patterns of tropopause height change are similar in “observations” (A) and a climate model (B)

A) ERA-40 trend (1979-2001)



B) PCM “All forcings” experiment



Blue and purple colors indicate an increase in height (decrease in pressure)

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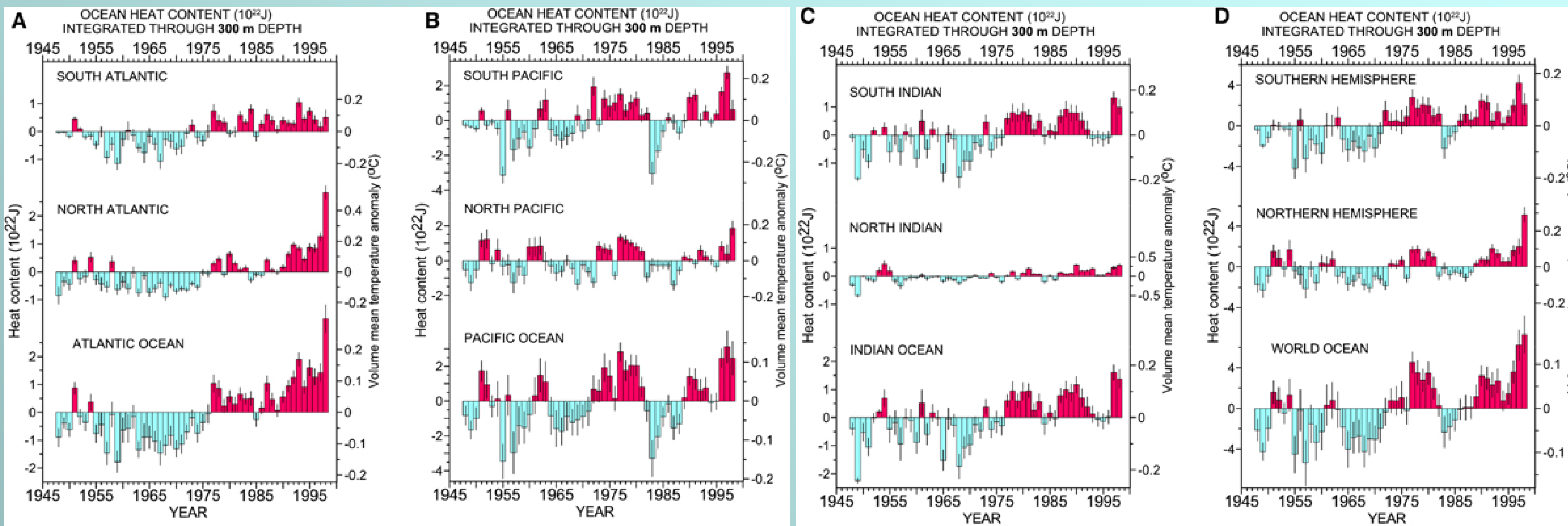
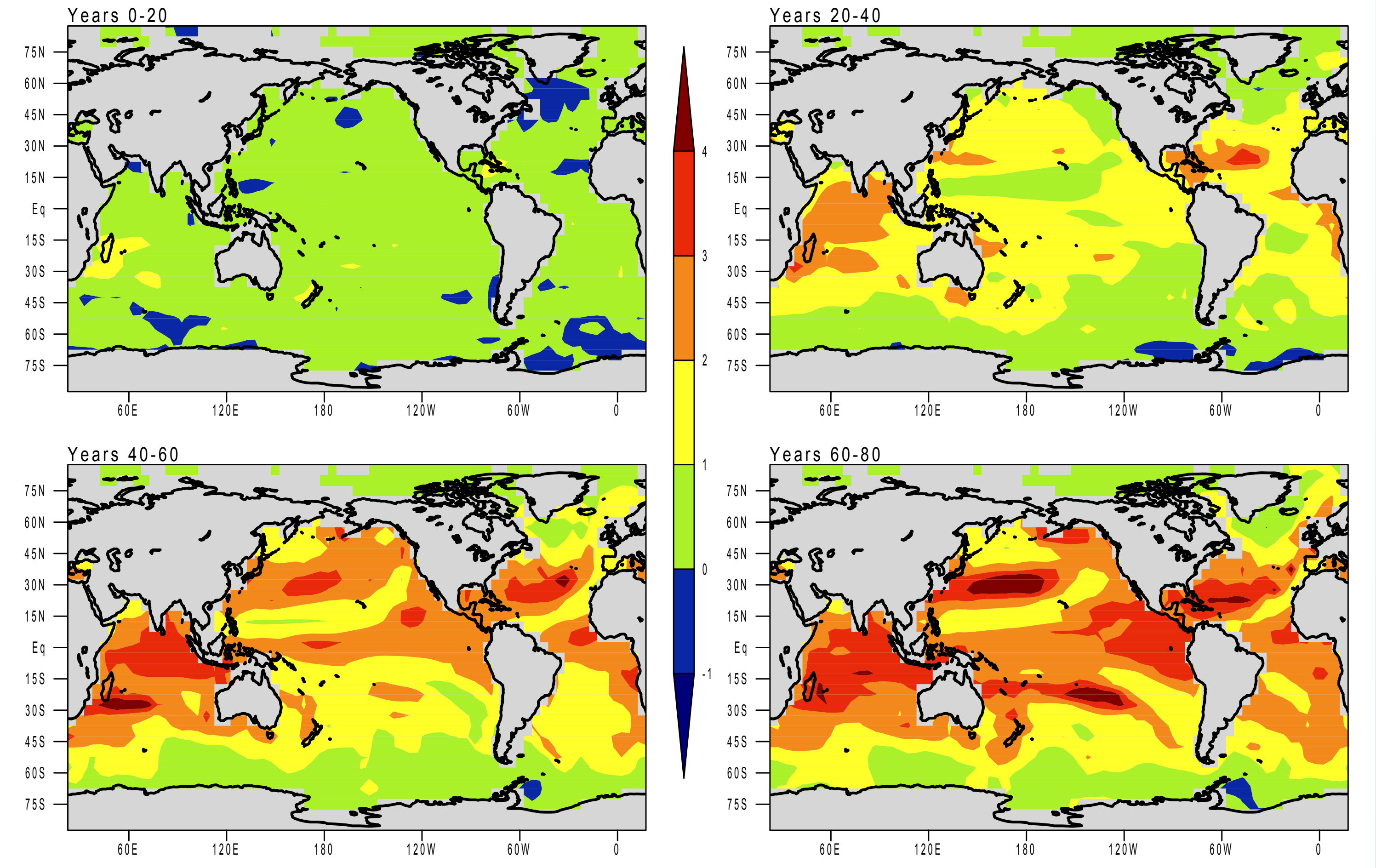
Warming of the world's oceans: Another "fingerprint" of human effects on climate



Levitus *et al.*, *Science* (2000)

The observed ocean warming is consistent with results from model simulations

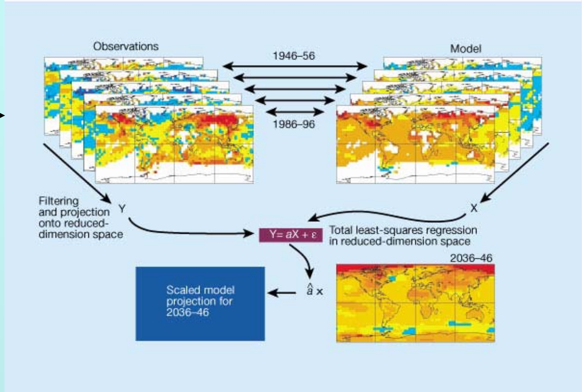
S/N ratio for change in mean ocean temperature (0-300m)



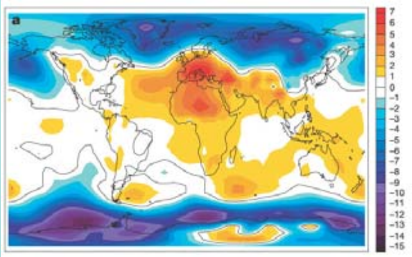
AchutaRao and Santer (in preparation)

“Fingerprints” of human effects on climate have been identified in many different variables

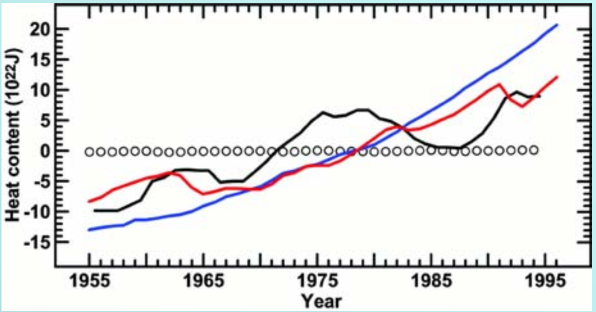
- Near-surface temperature



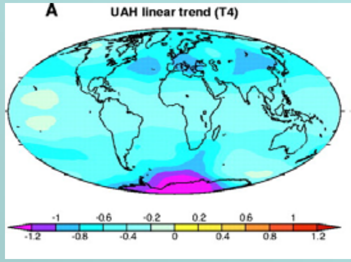
- Sea-level pressure



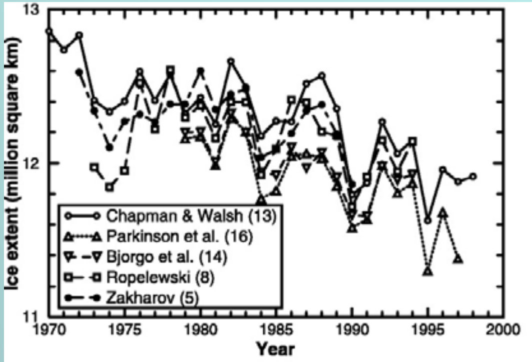
- Ocean heat content



- Atmospheric temperature



- Northern Hemisphere sea-ice extent



Emerging science: A selection of recently-published papers in *Science* and *Nature*

Global Warming and Northern Hemisphere Sea Ice Extent

Konstantin Y. Vinnikov,[1*] Alan Robock,[2] Ronald J. Stouffer,[3] John E. Walsh,[4] Claire L. Parkinson,[5] Donald J. Cavalieri,[5] John F. B. Mitchell,[6] Donald Garrett,[7] Victor F. Zakharov[8]

Surface and satellite-based observations show a decrease in Northern Hemisphere sea ice extent during the past 46 years. A comparison of these trends to control and transient integrations (forced by observed greenhouse gases and tropospheric sulfate aerosols) from the Geophysical Fluid Dynamics Laboratory and Hadley Centre climate models reveals that the observed decrease in Northern Hemisphere sea ice extent agrees with the transient simulations, and both trends are much larger than would be expected from natural climate variations. From long-term control runs of climate models, it was found that the probability of the observed trends resulting from natural climate variability, assuming that the models' natural variability is similar to that found in nature, is less than 2 percent for the 1978–98 sea ice trends and less than 0.1 percent for the 1953–98 sea ice trends. Both models used here project continued decreases in sea ice thickness and extent throughout the next century.

Detection of Anthropogenic Climate Change in the World's Oceans

Tim P. Barnett,* David W. Pierce, Reiner Schnur

Large-scale increases in the heat content of the world's oceans have been observed to occur over the last 45 years. The horizontal and temporal character of these changes has been closely replicated by the state-of-the-art Parallel Climate Model (PCM) forced by observed and estimated anthropogenic gases. Application of optimal detection methodology shows that the model-produced signals are indistinguishable from the observations at the 0.05 confidence level. Further, the chances of either the anthropogenic or observed signals being produced by the PCM as a result of natural, internal forcing alone are less than 5%. This suggests that the observed ocean heat-content changes are consistent with those expected from anthropogenic forcing, which broadens the basis for claims that an anthropogenic signal has been detected in the global climate system. Additionally, the requirement that modeled ocean heat uptakes match observations puts a strong, new constraint on anthropogenically forced climate models. It is unknown if the current generation of climate models, other than the PCM, meet this constraint.

Anthropogenic Influence on the Autocorrelation Structure of Hemispheric-Mean Temperatures

T. M. L. Wigley,* R. L. Smith, B. D. Santer

It is shown that lagged correlations for and cross-correlations between observed hemispheric-mean temperature data differ markedly from those for unforced (control-run) climate model simulations. The differences can be explained adequately by assuming that the observed data contain a significant externally forced component involving both natural (solar) and anthropogenic influences and that the global climate sensitivity is in the commonly accepted range. Solar forcing alone cannot reconcile the differences in autocorrelation structure between observations and model control-run data.

Anthropogenic Warming of Earth's Climate System

Sydney Levitus,[1*] John I. Antonov,[1] Julian Wang,[2] Thomas L. Delworth,[3] Keith W. Dixon,[3] Anthony J. Broccoli[3]

We compared the temporal variability of the heat content of the world ocean, of the global atmosphere, and of components of Earth's cryosphere during the latter half of the 20th century. Each component has increased its heat content (the atmosphere and the ocean) or exhibited melting (the cryosphere). The estimated increase of observed global ocean heat content (over the depth range from 0 to 3000 meters) between the 1950s and 1990s is at least one order of magnitude larger than the increase in heat content of any other component. Simulation results using an atmosphere-ocean general circulation model that includes estimates of the radiative effects of observed temporal variations in greenhouse gases, sulfate aerosols, solar irradiance, and volcanic aerosols over the past century agree with our observation-based estimate of the increase in ocean heat content. The results we present suggest that the observed increase in ocean heat content may largely be due to the increase of anthropogenic gases in Earth's atmosphere.

Detection of a Human Influence on North American Climate

David J. Karoly,[1*] Karl Braganza,[2] Peter A. Stott,[3,5†] Julie M. Arblaster,[4] Gerald A. Meehl,[4] Anthony J. Broccoli,[5†] Keith W. Dixon[5]

Several indices of large-scale patterns of surface temperature variation were used to investigate climate change in North America over the 20th century. The observed variability of these indices was simulated well by a number of climate models. Comparison of index trends in observations and model simulations shows that North American temperature changes from 1950 to 1999 were unlikely to be due to natural climate variation alone. Observed trends over this period are consistent with simulations that include anthropogenic forcing from increasing atmospheric greenhouse gases and sulfate aerosols. However, most of the observed warming from 1900 to 1949 was likely due to natural climate variation.

Climate Effects of Black Carbon Aerosols in China and India

Surabi Menon,[1,2*] James Hansen,[1] Larissa Nazarenko,[1,2] Yunfeng Luo[3]

In recent decades, there has been a tendency toward increased summer floods in south China, increased drought in north China, and moderate cooling in China and India while most of the world has been warming. We used a global climate model to investigate possible aerosol contributions to these trends. We found precipitation and temperature changes in the model that were comparable to those observed if the aerosols included a large proportion of absorbing black carbon ("soot"), similar to observed amounts. Absorbing aerosols heat the air, alter regional atmospheric stability and vertical motions, and affect the large-scale circulation and hydrologic cycle with significant regional climate effects.

Rapid Thinning of Parts of the Southern Greenland Ice Sheet

W. Krabill,[1*] E. Frederick,[2] S. Manizade,[2] C. Martin,[2] J. Sonntag,[2] R. Swift,[2] R. Thomas,[2] W. Wright,[1] J. Yungel[2]

Aircraft laser-altimeter surveys over southern Greenland in 1993 and 1998 show three areas of thickening by more than 10 centimeters per year in the southern part of the region and large areas of thinning, particularly in the east. Above 2000 meters elevation the ice sheet is in balance but thinning predominates at lower elevations, with rates exceeding 1 meter per year on east coast outlet glaciers. These high thinning rates occur at different latitudes and at elevations up to 1500 meters, which suggests that they are caused by increased rates of creep thinning rather than by excessive melting. Taken as a whole, the surveyed region is in negative balance.

Contributions of Anthropogenic and Natural Forcing to Recent Tropopause Height Changes

B. D. Santer,[1*] M. F. Wehner,[2] T. M. L. Wigley,[3] R. Sausen,[4] G. A. Meehl,[3] K. E. Taylor,[1] C. Ammann,[3] J. Arblaster,[3] W. M. Washington,[3] J. S. Boyle,[1] W. Brüggemann[5]

Observations indicate that the height of the tropopause—the boundary between the stratosphere and troposphere—has increased by several hundred meters since 1979. Comparable increases are evident in climate model experiments. The latter show that human-induced changes in ozone and well-mixed greenhouse gases account for ~80% of the simulated rise in tropopause height over 1979–1999. Their primary contributions are through cooling of the stratosphere (caused by ozone) and warming of the troposphere (caused by well-mixed greenhouse gases). A model-predicted fingerprint of tropopause height changes is statistically detectable in two different observational ("reanalysis") data sets. This positive detection result allows us to attribute overall tropopause height changes to a combination of anthropogenic and natural external forcings, with the anthropogenic component predominating.

External Control of 20th Century Temperature by Natural and Anthropogenic Forcings

Peter A. Stott,[1*] S. F. B. Tett,[1] G. S. Jones,[1] M. R. Allen,[2] J. F. B. Mitchell,[1] G. J. Jenkins[1]

A comparison of observations with simulations of a coupled ocean-atmosphere general circulation model shows that both natural and anthropogenic factors have contributed significantly to 20th century temperature changes. The model successfully simulates global mean and large-scale land temperature variations, indicating that the climate response on these scales is strongly influenced by external factors. More than 80% of observed multidecadal-scale global mean temperature variations and more than 60% of 10- to 50-year land temperature variations are due to changes in external forcings. Anthropogenic global warming under a standard emissions scenario is predicted to continue at a rate similar to that observed in recent decades.

Warming of the World Ocean

Sydney Levitus,* John I. Antonov, Timothy P. Boyer, Cathy Stephens

We quantify the interannual-to-decadal variability of the heat content (mean temperature) of the world ocean from the surface through 3000-meter depth for the period 1948 to 1998. The heat content of the world ocean increased by $\sim 2 \times 10^{23}$ joules between the mid-1950s and mid-1990s, representing a volume mean warming of 0.06°C. This corresponds to a warming rate of 0.3 watt per meter squared (per unit area of Earth's surface). Substantial changes in heat content occurred in the 300- to 1000-meter layers of each ocean and in depths greater than 1000 meters of the North Atlantic. The global volume mean temperature increase for the 0- to 300-meter layer was 0.31°C, corresponding to an increase in heat content for this layer of $\sim 10^{23}$ joules between the mid-1950s and mid-1990s. The Atlantic and Pacific Oceans have undergone a net warming since the 1950s and the Indian Ocean has warmed since the mid-1960s, although the warming is not monotonic.

Causes of Climate Change Over the Past 1000 Years

Thomas J. Crowley

Recent reconstructions of Northern Hemisphere temperatures and climate forcing over the past 1000 years allow the warming of the 20th century to be placed within a historical context and various mechanisms of climate change to be tested. Comparisons of observations with simulations from an energy balance climate model indicate that as much as 41 to 64% of preanthropogenic (pre-1850) decadal-scale temperature variations was due to changes in solar irradiance and volcanism. Removal of the forced response from reconstructed temperature time series yields residuals that show similar variability to those of control runs of coupled models, thereby lending support to the models' value as estimates of low-frequency variability in the climate system. Removal of all forcing except greenhouse gases from the ~1000-year time series results in a residual with a very large late-20th-century warming that closely agrees with the response predicted from greenhouse gas forcing. The combination of a unique level of temperature increase in the late 20th century and improved constraints on the role of natural variability provides further evidence that the greenhouse effect has already established itself above the level of natural variability in the climate system. A 21st-century global warming projection far exceeds the natural variability of the past 1000 years and is greater than the best estimate of global temperature change for the last interglacial.

Rapid Bottom Melting Widespread near Antarctic Ice Sheet Grounding Lines

Eric Rignot[1*] and Stanley S. Jacobs[2*]

As continental ice from Antarctica reaches the grounding line and begins to float, its underside melts into the ocean. Results obtained with satellite radar interferometry reveal that bottom melt rates experienced by large outlet glaciers near their grounding lines are far higher than generally assumed. The melting rate is positively correlated with thermal forcing, increasing by 1 meter per year for each 0.1°C rise in ocean temperature. Where deep water has direct access to grounding lines, glaciers and ice shelves are vulnerable to ongoing increases in ocean temperature.

Detection of human influence on sea-level pressure

Nathan P. Gillett*, Francis W. Zwiers†, Andrew J. Weaver* & Peter A. Stott‡

* *School of Earth and Ocean Sciences, University of Victoria, PO Box 3055, Victoria, British Columbia, V8W 3P6, Canada*

† *Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, PO Box 1700, STN CSC, Victoria, British Columbia, V8W 2Y2, Canada*

‡ *Hadley Centre for Climate Prediction and Research, Met Office, Bracknell, Berkshire RG12 2SY, UK*

Greenhouse gases and tropospheric sulphate aerosols—the main human influences on climate—have been shown to have had a detectable effect on surface air temperature[1–3], the temperature of the free troposphere and stratosphere[2,4] and ocean temperature[5,6]. Nevertheless, the question remains as to whether human influence is detectable in any variable other than temperature. Here we detect an influence of anthropogenic greenhouse gases and sulphate aerosols in observations of winter sea-level pressure (December to February), using combined simulations from four climate models. We find increases in sea-level pressure over the subtropical North Atlantic Ocean, southern Europe and North Africa, and decreases in the polar regions and the North Pacific Ocean, in response to human influence. Our analysis also indicates that the climate models substantially underestimate the magnitude of the sea-level pressure response. This discrepancy suggests that the upward trend in the North Atlantic Oscillation index[7] (corresponding to strengthened westerlies in the North Atlantic region), as simulated in a number of global warming scenarios[8–10], may be too small, leading to an underestimation of the impacts of anthropogenic climate change on European climate.

Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations

Cecile Cabanes, Anny Cazenave, Christian Le Provost

The 3.2 ± 0.2 millimeter per year global mean sea level rise observed by the Topex/Poseidon satellite over 1993–98 is fully explained by thermal expansion of the oceans. For the period 1955–96, sea level rise derived from tide gauge data agrees well with thermal expansion computed at the same locations. However, we find that subsampling the thermosteric sea level at usual tide gauge positions leads to a thermosteric sea level rise twice as large as the "true" global mean. As a possible consequence, the 20th century sea level rise estimated from tide gauge records may have been overestimated.

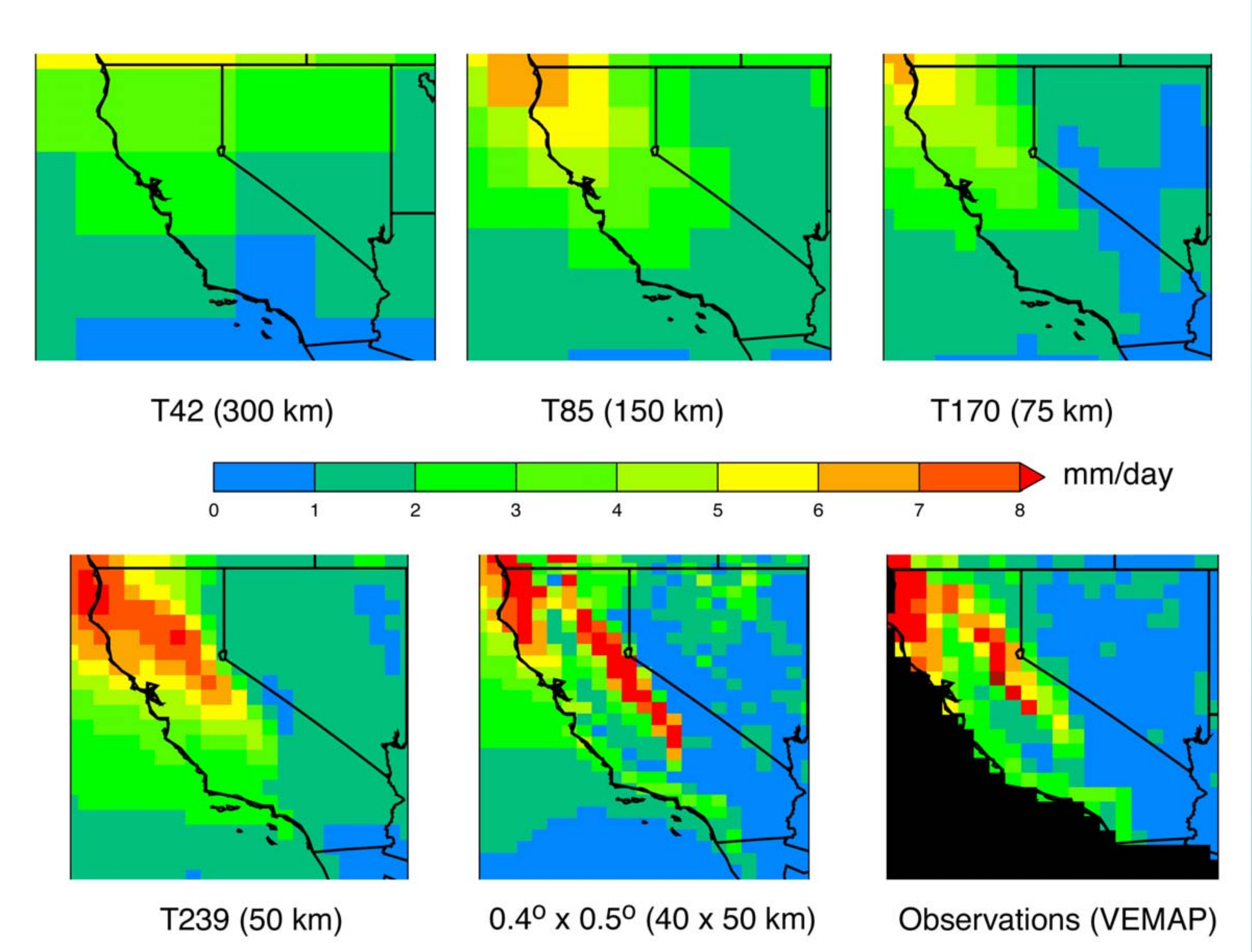
Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level

Anthony A. Arendt,* Keith A. Echelmeyer, William D. Harrison, Craig S. Lingle, Virginia B. Valentine

We have used airborne laser altimetry to estimate volume changes of 67 glaciers in Alaska from the mid-1950s to the mid-1990s. The average rate of thickness change of these glaciers was −0.52 m/year. Extrapolation to all glaciers in Alaska yields an estimated total annual volume change of −52 ± 15 km^3/year (water equivalent), equivalent to a rise in sea level (SLE) of 0.14 ± 0.04 mm/year. Repeat measurements of 28 glaciers from the mid-1990s to 2000–2001 suggest an increased average rate of thinning, −1.8 m/year. This leads to an extrapolated annual volume loss from Alaska glaciers equal to −96 ± 35 km^3/year, or 0.27 ± 0.10 mm/year SLE, during the past decade. These recent losses are nearly double the estimated annual loss from the entire Greenland Ice Sheet during the same time period and are much higher than previously published loss estimates for Alaska glaciers. They form the largest glaciological contribution to rising sea level yet measured.

Climate model resolution is improving, leading to improved performance

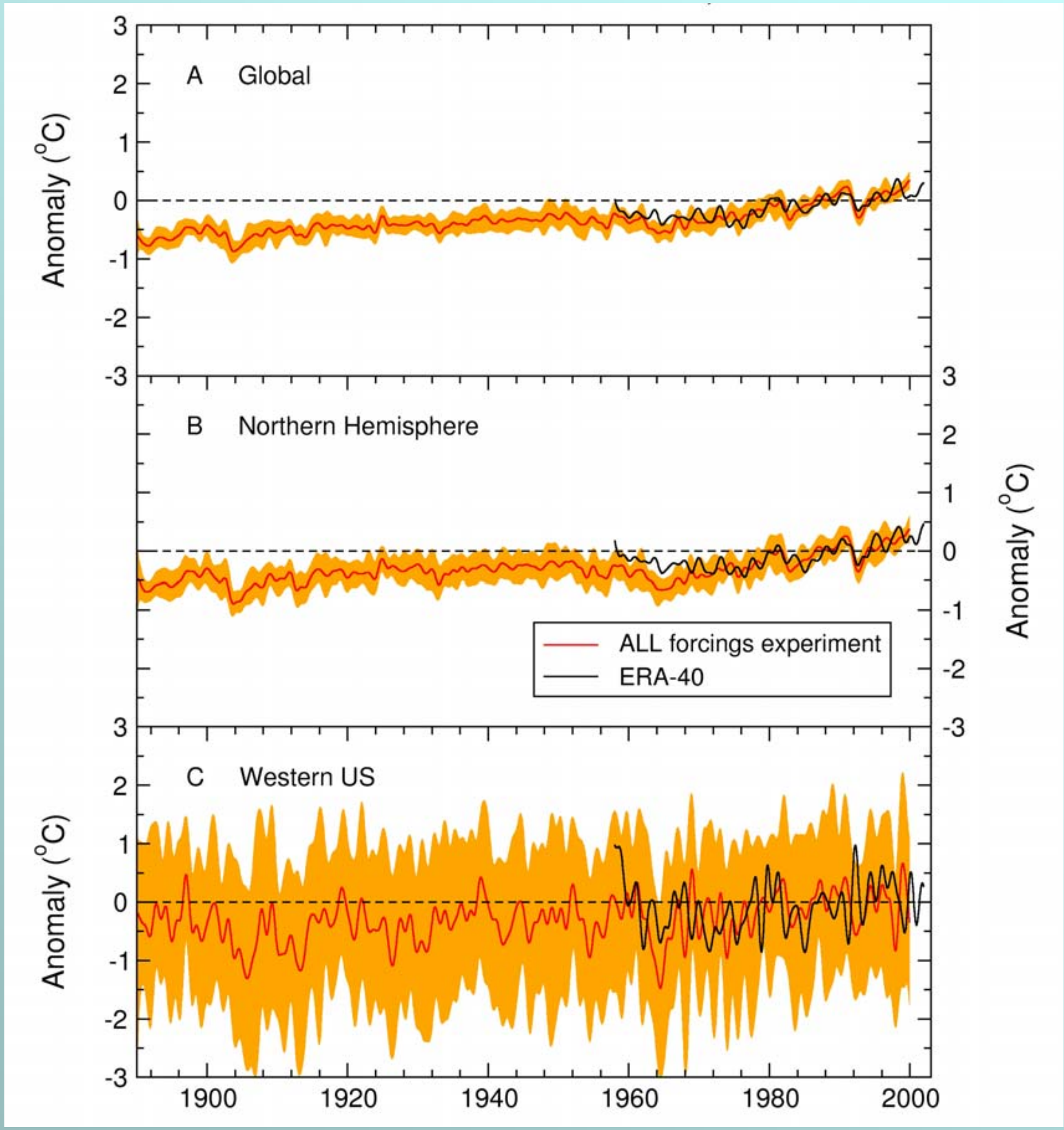
Duffy *et al*.



PCMDI

We are now trying to detect human-induced climate change at regional scales

Near-surface temperature changes



Why should we focus on regional climate?

- **Because humans and natural ecosystems experience regional, not global, climate;**
- **Because improvements in climate models make meaningful regional projections possible**
- **Regional climate changes will determine societal impacts and drive climate-related policy decisions**

Water availability

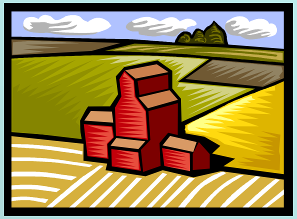
Recreation

Extreme events

Air quality

Human health

Agriculture



Conclusions

- **We have identified human-caused climate change in a number of different aspects of the climate system**

- **The climate system is telling us a robust, internally–consistent story**

- **Ultimately, the electorate will decide how to respond to human-induced climate change**

  - To make wise decisions, we need an informed, scientifically-savvy electorate

  - This will require substantial investments in educational outreach

- **We need to improve our ability to predict the regional-scale climate changes that are "in the pipeline", and their societal impacts**

  - It is these regional-scale changes that we will "feel" most strongly

Future work: Use common historical forcing scenarios

- **IPCC requests that modeling groups perform common scenario calculations for future emissions of trace gases and aerosols**
  - ***e.g.***, Stabilization and “commitment” calculations
- **No requirement for calculations with common estimates of <u>historical</u> forcings**
  - Well-mixed GHGs, ozone, volcanic aerosols, solar irradiance changes
  - Anthropogenic aerosols?
- **This hampers intercomparison and interpretation of differences in model responses to historical forcings**
  - Without common historical forcing scenarios, model comparisons in IPCC 2007 will be convolving differences in both applied forcings and simulated responses!
- **We can and should do better than the CMIP2 comparisons shown in IPCC 2001**

Future work: Search for “fingerprints” of anthropogenic aerosols in observations

- **Most statistical “fingerprint” detection studies have considered only direct scattering effects of anthropogenic sulfate aerosols**
  - Few studies have incorporated sulfate aerosol indirect effects, or direct/indirect effects from soot and biomass aerosols, mineral dust, ***etc.***
- **This leaves current detection work open to justifiable criticism – a potential problem for IPCC 2007**
- **High priority to repeat detection and attribution studies with best estimates of climate fingerprints arising from soot, biomass, and mineral dust aerosols**
  - We should be able to identify these fingerprints if they are as large as hypothesized
  - Some of these forcings should have signals with great regional and seasonal specificity!